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LCA FOR WOOD

Environmental footprints of British Columbia wood pellets from a simplified life cycle analysis

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Abstract
Purpose Environmental footprints of wood pellets produced in British Columbia (BC) of Canada are to be estimated based on industry surveys and published emission factor data.
Method The streamlined life cycle analysis starts from raw material acquisition and ends at port Rotterdam in Europe for exported pellets or North Vancouver port for domestically used pellets. The raw materials used for pellet production are dry and wet sawmill residues, and allocations are based on dry mass. The pellet production data are based on three pellets mills in western Canada.
Results and discussion For every tonne of BC pellets exported, 295 kg CO_2 equivalent greenhouse gases is released. The human health, ecosystem quality, and climate change impacts of the exported pellets can be reduced by 61%, 66%, and 53%, respectively, if the pellets stay in BC for local applications. Harvesting is the second highest impacting process, following marine transportation. The total amount of primary energy consumed for 1 tonne of exported pellets is 6,372 MJ, and approximately 35% of it is attributed to marine transportation. Exported pellets have 16.4% of nonrenewable energy content and an energy penalty of 33% with energy penalty defined as the amount of primary energy consumed to produce and deliver one unit of process energy using the higher heating value. For domestically used pellets, the energy penalty is 21% and the nonrenewable energy content is 8.59%.
Conclusions Marine transportation is the main contributor for all impact categories. Improving the energy efficiency of the harvesting and pellet plant operations is also a way to effectively reduce these wood pellet's environmental footprints.

Keywords British Columbia · Impact assessment · Life cycle assessment (LCA) · Wood pellets · Wood residues

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1 Introduction

Biomass has been receiving a lot of attention as an alternative energy source due to its abundance and carbon-neutral characteristics. However, the linkage between biofuel and food prices has promoted the shift of biofuel raw material to organic materials that are not suitable as food for humans, such as lignocellulosic biomass. Lignocellulosic biomass can be converted to various forms of energy via thermal–chemical, chemical, and biochemical processes; however, the environmental footprints of these bioenergy compared to conventional energy products in terms of pollutant emissions

and primary energy consumptions during their production, delivery, and usage still need to be investigated. This task is often done using life cycle analysis, also known as LCA (Batan et al. 2010; Campbell et al. 2011; Clarens et al. 2010; Felder and Dones 2007; Lardon et al. 2009; Melamu and von Blottnitz 2009; von Blottnitz and Curran 2007; Zhang et al. 2010).

Recent focus on lignocellulosic biomass feedstock results in elevated interest in waste woody biomass, especially in western Canada due to its abundant woody biomass resources. One important issue related to woody biomass utilization is its high moisture content. Moisture not only adds to the weight and volume, thus increased transportation cost; it also lowers combustion efficiency. To improve the feedstock quality and to increase the volumetric energy density, woody biomasses are commonly pretreated (drying) and densified into briquettes and pellets. Pellets are smaller compared to briquettes and are used in specialized units equipped with automatic feeding systems while briquettes can be used as regular firewood in existing units. In most cases, wood pellets in Canada are made of sawdust or shavings.

In 2008, about 1.4 million metric tonnes of wood pellets was produced in Canada. Unlike the USA and most of the European countries where the majority of their pellets are for domestic market, about 90% of the Canadian wood pellets were exported (Melin 2008; Spelter and Toth 2009). In 2008, 70% of the Canadian wood pellets were shipped to Europe to satisfy their market demands (Melin 2008). Most European countries have high demand for renewable energy due to their stringent policies related to climate change, such as the ambitious energy and climate change objective set by the European Council in 2007, where they want to increase the share of renewable energy to 20% by 2020 (European Commission 2011).

As wood pellets are a common fuel source in Europe, there have been several studies on the LCA of wood pellets. For instance, in 2003, a study looked into the LCA of electricity production in Netherlands with coal co-combustion with either wood pellets from Canada or palm kernel shells from Malaysia (Damen and Faaij 2003). The report stated that pellets and palm kernel shells were better exported than to be utilized domestically for power generation due to the lower efficiencies of the relatively small-scale systems in Malaysia and Canada, the avoided coal mining and transportation to Netherlands, and the greener electricity mix in Canada. Another work published in 2000 investigated the transport chain of biomass, including wood pellets, for energy generation. It was concluded that when traveling interregionally at approximately 1,500 km, wood pellets would still have their environmental benefits, provided modern carriers are used (Forsberg 2000).

A more recent work focuses on the international logistics of wood pellets for various applications such as district heating, residential heating, and power generation in Europe (Sikkema et al. 2010). One of the case studies involves Canadian pellets for power generation in the Netherlands. It was concluded that 1,937 kg of CO_2 equivalent can be avoided per tonne of pellets used for electricity generation in the Netherlands and that pellets can achieve substantial GHG savings although they are much more expensive than fossil fuels such as coal.

A recently published work (Magelli et al. 2009) assessed the carbon footprint and the environmental impacts of Canadian wood pellets using a streamlined LCA, not accounting for land usage and infrastructure. Two pellet production scenarios with different fuel for the drying operation, one with unprocessed sawdust and the other with natural gas, were evaluated. This work demonstrated that pellets produced in BC and exported to Stockholm have a positive net energy with an energy penalty, defined as the primary energy required to produce and to transport the fuel pellet divided by the energy content of the pellet itself (using higher heating values), of 39%. Out of the 7.2 GJ required for the production and transportation of 1 tonne of pellets, 2.6 GJ is related to marine transportation. The data on energy consumption and emissions from the pellet plant were estimated based on densification process analysis instead of actual industry data. Transportation details such as traveling distances were based on actual pellet plants in BC. Comparing results from some of these existing studies on wood pellets LCA, it is observed that energy consumption during pellet plant operation varies greatly from 1,768 to 3,778 MJ/tonne of pellets (Hagberg et al. 2009; Magelli et al. 2009; Zhang et al. 2010; Świgoń and Longauer 2005).

There also exist discrepancies in the amount of fossil-based CO_2 emissions from different stages and the complete life cycle of the wood pellet based on different LCA studies. For instance, the emission associated with raw materials delivered to pellet plants varies from 34.5 to 63.4 kg CO_2/tonne of pellet equivalent and that the fossil CO_2 emission from the entire life cycle without transportation also ranges from 38 to 67 kg of CO_2/tonne of pellets (Hagberg et al. 2009; Magelli et al. 2009; Zhang et al. 2010). Based on these observations, it is concluded that in order to improve the estimate of the environmental footprints of BC wood pellet, it is important to perform a wood pellet LCA based on up-to-date data specific to BC conditions and practices.

To improve the data quality related to the pellet manufacturing at pellet plants in BC, industrial surveys have been conducted in this study among a number of pellet plants in BC and a shipping port in BC with the assistance of the Wood Pellet Association of Canada. The survey results in combination with updated emission factors for upstream processes, more detailed raw material and pellet logistics, more thorough moisture, and primary energy consumption calculations allow for the construction of an updated life cycle inventory

(LCI) database that captures the current pellet production and logistics in BC. The LCI database is imported into a commercial LCA software, SimaPro, in order to use its built-in impact assessment method to estimate the environmental footprints of BC wood pellets. The LCA performed here does not consider changes in land use and building infrastructure.

The objective is to quantify the environmental profile associated with each metric tonne of BC wood pellets exported to Europe in terms of human health, ecosystem quality, and climate change impacts. The total and stage-wise primary energy consumption, from both renewable and nonrenewable sources, energy penalty and nonrenewable energy content of the exported wood pellets are calculated to identify the hot spots in the whole production and supply chain. Lastly, the energy penalty and environmental footprints of Europe-bound and domestic pellets are also compared to each other. The streamlined LCA performed follows the framework presented in ISO 14040.

2 Method

BC wood pellets are generally produced from dry and wet sawmill residues, thus the processing stages included in the LCA of exported BC pellets are the harvesting of woody material in the forest, sawmill operation, pellet plant operation, port operation in North Vancouver, and all the transportation segments connecting the different stages. The system boundary for the exported pellets' LCA is from the harvesting of woody material to the arrival of wood pellets in Port Rotterdam in Netherlands, a major receiving port in Europe for Canadian wood pellets. The LCA for nonexported BC pellets is identical to that of the exported BC pellets except that port operation and marine transportation are omitted. Figure 1 shows the system boundary and identifies the different processing stages and transportation segments involved in the LCA for BC wood pellets exported to Rotterdam. Figure 1 also illustrates the types of energy considered in this LCA and how they are incorporated into the LCA. For instance, electricity in BC is generated from a variety of energy sources, but in the foreground system, namely the actual process of producing and transporting the wood pellets, not only electricity but also other forms of energy products are utilized. The emissions associated with the production and transportation of these energy products are considered as the background system.

As sawmill residues are by-products from the sawmill operations, allocations need to be performed. All allocations in this work are based on dry mass to provide a more conservative estimate as oppose to market value-based allocation where residues are usually assigned zero energy consumptions and impacts. The decision of using mass-based allocation is consistent with Jungmrirt et al. (2002) who concluded that mass-based allocation is the most practical allocation method in LCA of wood-based products for all of forestry, sawmill, and wood industry. The functional unit for both systems is 1 tonne of wood pellets.

The LCA performed here does not consider changes in land use and building infrastructure. As nearly 60% of BC land is covered by forest, and logging occurs in less than one third of 1% of BC's forests each year, generally no land is being converted into forest for logging purposes (B.C. Ministry of Forests, Mines and Land 2010; British Columbia Ministry of Forests 2003). Thus no changes in land use are considered. As the forest being logged was previously forest already, the effect on biodiversity due to land occupation and land use change is not applicable. However, logging practices may also have an effect on biodiversity but it is not taken into account in this work. Moreover, impacts of infrastructure can generally be approximated to be an additional

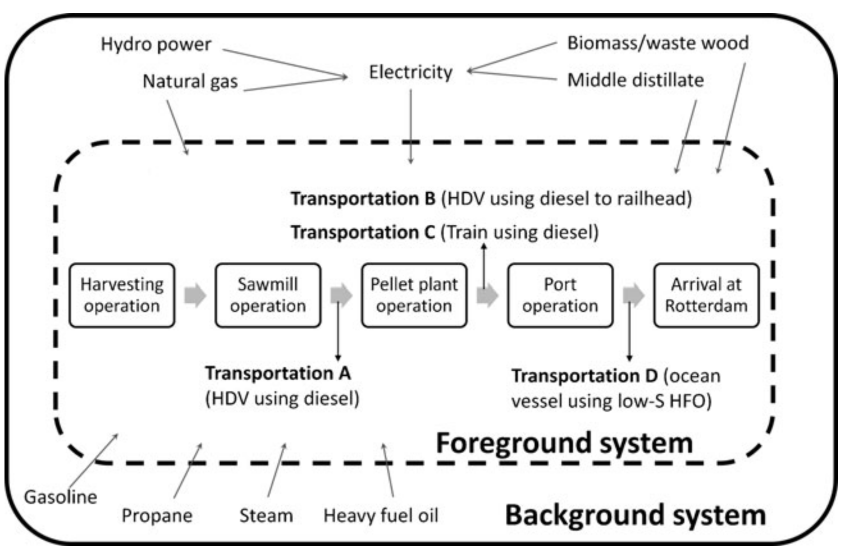


Fig. 1 System boundary for the streamlined LCA performed for BC wood pellets exported to Rotterdam

10% onto the overall values for wood products (Swiss Centre for Life Cycle Inventories 2007).

2.1 Life cycle inventory data

The first step is to obtain energy consumption data for each processing stage and transportation segment. The types of energy consumption considered are electricity, natural gas, heavy fuel oil (HFO), middle distillate (diesel), propane, steam, wood waste, and gasoline. Electricity is based on BC electricity mix 2006 (Environment Canada 2008) and more details are presented in the "Electronic supplementary material."

This study covers two types of energy consumption. The first type is secondary energy consumption which keeps track of energy consumed in the form of energy product such as electricity or fuel for the vehicles or equipment. Survey results from pellet plants and port operations are all secondary energy consumptions. The other type of energy consumption is primary energy consumption, which also includes the amount of energy required to produce an energy product such as electricity and fuels. For LCA, the primary energy consumption is often more relevant as the calculation of the primary energy consumption itself requires LCA. In this study, primary energy is divided into renewable and nonrenewable sources where the latter includes both fossil fuels and nuclear power. Primary energy requirement for different types of energy and fuels is obtained from the Ecoinvent database (Swiss Centre for Life Cycle Inventories 2007) in Simapro or from GHGenius v3.17 (Delucchi and Levelton 2010). Ecoinvent database is based on European data while GHGenius v3.17 is based on Canadian values. Some Ecoinvent data (such as for steam production and obtaining biomass for BC electricity generation) are modified so that US electricity profile instead of European electricity profile is utilized, and these data are collectively called the US-EI database (Swiss Centre for Life Cycle Inventories et al. 2008). Whenever available, the US-EI database is used instead of the Ecoinvent database. However, as US electricity generally relies more on fossil fuels, the primary energy requirements presented might have overestimated the amount of nonrenewable energy used in the actual lifecycle of BC pellets as discussed in this study. The emissions from each processing stage and transportation segment are obtained by multiplying each type of secondary energy consumption with its respective emission factors. For each type of secondary energy, there is an emission factor for each of the pollutants being investigated. Each emission factor consists of upstream and usage emission factors where the first value accounts for emissions associated with the production and transportation of the energy while the second factor relates to the emissions produced during fuel usage. For processing stages, the emission factors are in the unit of kilograms of pollutant emitted per megajoule of energy input. For transportation segments, the emissions are given in kilograms of pollutant emitted per tonne-kilometer where tonne-kilometer is traveling 1 km with 1 tonne of load. As emission factors depend on the method of fuel usage, emission factors for transportation depend on the type of vehicles used. The "Electronic supplementary material" describes the sources of emission factors and primary energy requirement for all types of energy consumption considered in this study. Note that all energy units considered here referred to higher heating value (HHV).

The emission species investigated in the study are fossil CO_2, biogenic CO_2, generic CH_4, biogenic CH_4, N_2O, generic CO, biogenic CO, non-methane volatile organic compounds (NMVOC), NO_X in NO_2 equivalent, SO_X in SO_2 equivalent, particulate matters (PM) and $PM_{2.5}$. The growth of biomass was not assigned upstream carbon sequestration credits. Thus, organic carbon absorption was not modeled but the emission of carbon dioxide during the combustion of this biomass was calculated based on the carbon content of the biomass and was branded as "biogenic CO_2." Biogenic and fossil-based CO_2, CH_4, and CO emissions are segregated in the US-EI database while GHGenius v3.17 is only capable of separating biogenic and fossil-based emissions for CO_2 but not for CH_4 and CO. Due to this reason, CH_4 and CO emissions from GHGenius v3.17 are branded "generic," implying that a small portion of them may be biogenic. However, when performing impact assessments, these generic emissions are considered to have fossil fuel origins.

Another pollutant which requires special attention is PM. In all cases, only one of PM or $PM_{2.5}$ should be included in the calculation since $PM_{2.5}$ is a subcategory of PM. Comparing PM and $PM_{2.5}$ emissions, it is often more beneficial to know the $PM_{2.5}$ emission as $PM_{2.5}$ is the portion that has the most significant impact on human health according to IMPACT 2002+, the impact assessment method to be used (Humbert et al. 2005; Jolliet et al. 2003). In fact, the health impact factor of PM in IMPACT 2002+ is approximated to be a fraction of $PM_{2.5}$, which works out to be 0.33 kg $PM_{2.5}$ eq/kg PM, with each kilogram $PM_{2.5}$eq equal to 7.00E-4 DALY in IMPACT 2002+. The 0.33 value is based on the typical ratio of $PM_{2.5}$ to PM in air (Humbert et al. 2005). However, GHGenius v3.17 and many other sources only have emission factors for PM instead of $PM_{2.5}$. Due to this limitation, either PM or $PM_{2.5}$ is reported based on data availability but care was taken so that not both emissions are included for a single process. In this study, the only process with a $PM_{2.5}$ emission factor is steam generation. Unfortunately, impact factors do not specify the archetype of the emissions, and the spatial differentiation should be considered in the future work. Furthermore, although some

database provides a more detailed pollutant list, only those listed previously are included in this study for consistency.

The collected raw data (such as survey result including energy consumption and transportation data) and literature values (such as energy consumptions during different processing stages, emission factors, physical and chemical properties of the materials involved) were first entered into and organized in Excel for calculations of weight averages, allocation, and unit conversions. The stage-wise emissions based on emission factors and energy consumption data were first calculated in Excel as well. Emission factors and energy consumption data for each processing stage were then entered into SimaPro. The emission data calculated by SimaPro were then compared with those calculated with Excel to eliminate possible mistakes.

2.2 Processing stages

The amount of energy consumed during harvesting to produce one t of pellet is taken from Sambo (2002). This value includes the energy required for preharvest activities, logging, camp, silviculture, and the hauling of trees from the harvesting operation to the mill yard. Dry mass-based allocation is used and the details on the calculation are given in the "Electronic supplementary material."

For the sawmill operation, the energy consumption data is taken from the CIEEDAC (Canadian Industry End-Use Data and Analysis Centre) Report from Simon Fraser University (Nyboer 2008). The 2006 values, reported in megajoules per cubic meter of lumbers exiting the sawmill, are converted to megajoules per tonne of pellets, with details given in the "Electronic supplementary material." It is worth noting that some unit operations in the sawmill are not relevant to the production of sawdust (for instance, sawdust are collected before the drying process thus energy requirement for the dryer should not be included in the production of sawdust but only for shavings, which are produced after the logs are dried), but for this study, energy usage for all operations in the sawmill is included as the sawmill operation is treated as a whole with no segregations.

Energy consumptions in pellet plant in megajoules per tonne of wood pellets is obtained from industrial surveys conducted in 2008 to 2009 based on current technology with the help of the Wood Pellet Association of Canada. Three sets of pellet plant data were received, but since some data are more complete than others, some values used are weighted average of two plants instead of three plants. The weighting factors are based on each plant's contribution to the total production in the calculation. Based on the survey, the average moisture content of the raw materials received is 34% wet basis while the moisture content of pellets is taken to be 5.6% wet basis, based on the analysis performed on the pellets at shipping port. The energy consumption reported under this category does not include transportations to and from the pellet plants.

Energy consumptions reported for port operation include energy needed for loading, unloading, and transportation of pellets within port along with transportation within the port for daily operations. These data are based on survey results from one of the two major BC ocean port that specializes in the oversea shipping of wood materials, including wood pellets. The annual energy consumption from the surveyed port is divided by the annual amount of pellets entering the port for shipping to yield energy consumption per tonne of pellets.

Table 1 summarizes the secondary energy consumption data for each processing stage with the values converted to megajoules consumed per tonne of pellet produced in BC. Furthermore, the sources of emission factors used for this studies and the detail unit conversion to functional units for harvesting operation and sawmill operation can be found in the "Electronic supplementary material."

2.3 Transportation

The transportation between harvesting field and sawmill is already included in the harvesting data, and the rest of the transportation involved in this study is broken down into four segments: from sawmill to pellet plant (transportation A), from pellet plant to railhead (transportation B), from railhead to port (transportation C), and lastly from port in North Vancouver to Rotterdam (transportation D). The first two segments of transportation are via heavy-duty vehicles (HDV) such as trucks. Once arriving at the railhead, the transportation to the port is via train powered by diesel. During marine transportation, the fuel used for the bulk vessel is low sulfur (<1.5% S) HFO. Energy required for transportation A to D need to be estimated based on fuel efficiency for different modes of transportation. The values used for fuel efficiencies are presented in Table 1 in the "Electronic supplementary material" under "Notes." Using emission factors in the unit of kilogram of pollutant emitted per tonne-kilometer, total emissions can be calculated once the distance traveled is known. Since the functional unit for this analysis is 1 tonne of wood pellets, for transportation segments that involve the delivery of the pellets itself, emissions are obtained by simply multiplying the emission factors by the distance traveled. However, for transportation A, where the loads being transferred are wood residues that have different moisture content than wood pellets, a conversion factor needs to be included in the calculation as well. This conversion factor is the mass ratio of wood pellet to wood residue (both are "as received" instead of "bone dry"), which is 0.62 from the survey. The traveling distance for transportation A, B, C, and D are 25.6, 99.1, 840, and 16,668 km, respectively. For trucks, the emissions are based

Table 1 Stage-wise secondary energy consumption in the unit of MJ consumed per t of wood pellets

Type of energy consumed	Harvesting operation[a]	Sawmill operation[b]	Pellet plant operation[c]	Port operation[d]
Electricity	0	186	490	11.1
Natural gas	0	135	0	0
Heavy fuel oil	0	14.6	0	0
Middle distillates (diesel)	689	42.9	23.5	5.37
Propane	0	3.68	6.16	0
Steam	0	47.6	0	0
Wood waste	0	271	1,059	0
Gasoline	0	0	0	2.01

[a] From Sambo (2002)

[b] From CIEEDAC Report from Simon Fraser University (Nyboer 2008)

[c] From industry surveys

[d] From industry survey

on empty return trip (the way GHGenius was built). But for railway and marine transportation, their energy intensity (megajoules/tonne-kilometer) was derived from statistical data that included the total weight of good transported and the total amount of fuels consumed. The issue of percentage of load of return trips is thus already incorporated in the emission factors and reflects the average industrial practices in Canada's rail and marine transportation.

2.4 Impact assessments

IMPACT 2002+ (Jolliet et al. 2003) was selected for impact assessments in this case study as it includes both midpoint

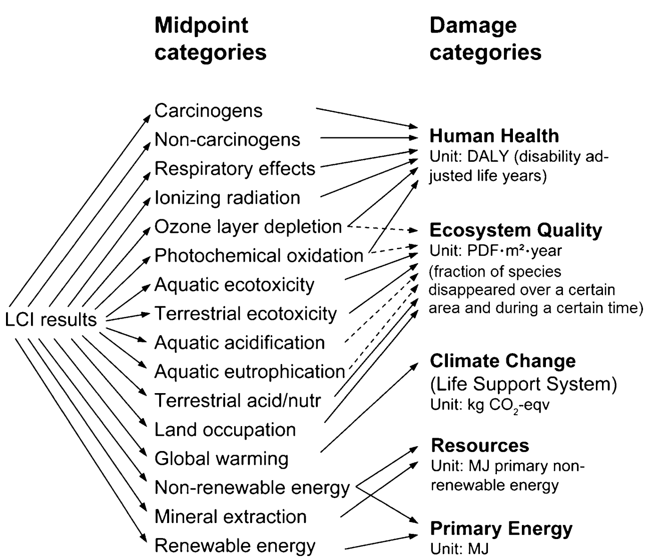


Fig. 2 Overall scheme of the IMPACT 2002+ framework with modifications made for this study (based on Jolliet et al. 2003)

and end point impacts. The most current version of IMPACT 2002+ at time of analysis (v2.06) is adapted for analysis with an extra category being added to keep track of the primary energy consumption throughout the life cycle, as shown in Fig. 2. The dashed lines indicate that the conversions into damage categories have not yet been properly established. The units used for each impact category, such as DALY and PDF in square meters per year, are also defined in Fig. 2. Moreover, when establishing processes in Simapro, land usages were not entered. Thus, the value for "land occupation" based on the IMPACT 2002+ analysis is zero.

The impacts of biogenic CH_4 and CO are added under the categories of respiratory organic and inorganic, respectively, using the impact values of their fossil fuel origin counterparts. Four end point categories, human health, ecosystem quality, climate change, and primary energy consumption are discussed in this study. Details on how the different damage categories are calculated can be found in the work of Jolliet et al. (2003). IMPACT 2002+ uses mostly the IPCC 2001 500-year time horizon global warming potential (GWP) factors, and some other built-in factors were calculated based on the 500-year GWP so these default values are used in this study for global warming impact assessment. According to Cherubini et al. (2011), by assuming a rotation year of 50 for the trees with carbon removal by biomass regrowth only, the GWP for biogenic CO_2 has a value of 0.16 because of the time delay in capturing the same amount of released CO_2 from the atmosphere by the regrowth of trees. However, in view of that, wood residues are waste materials which, if not recovered and used as biofuels, will decompose in the forest and release CO_2. One may also opt to calculate the GWP of biogenic CO_2 from burning wood pellets in comparison to the delayed release of CO_2 from decomposing wood residues. For the sake of simplification, GWP for biogenic CO_2 has been assigned a value of 0 in this study.

Moreover, it is important to keep in mind that IMPACT 2002+ was developed in Europe so the values of parameters used for the compilation of human toxicity are calculated at a continental level for Western Europe. Therefore, the final values to be presented here only serve as indicators for scenario comparisons as the absolute values do not capture the geographical and ecological differences between western Canada and Western Europe. Furthermore, the effects of emission locations or spatial variations are not considered in this analysis.

2.5 Energy content

Primary energy consumption data are used to calculate the energy penalty of wood pellet that are delivered to North Vancouver or Rotterdam. This is done by dividing total primary energy consumption required to produce and deliver 1 tonne of wood pellet by the HHV of the wood pellets. The HHV of wood pellet used in calculations is 19.4 MJ/kg

Table 2 Stage-wise and life cycle emissions and energy consumptions for exported pellets arriving in Rotterdam and pellets arriving in North Vancouver

	Processing stages				Transportation				Total		Reduction (%)
	Harvesting operation	Sawmill operation	Pellet plant operation	Port operation	A, to pellet mill via HDV	B, to railhead via HDV	C, to port via train	D, marine transportation	Export pellet	Local[a]	
Air emission (kg/tonne)											
All CO_2	62.80	46.39	110.34	0.88	7.92	19.11	17.19	152.31	417	264	36.7
CO_2, fossil	62.38	19.66	8.33	0.76	7.87	18.98	17.07	151.45	286	134	53.1
CO_2, biogenic	0.43	26.73	102.01	0.12	0.05	0.13	0.12	0.86	130	129	0.7
All CH_4	8.94E−02	4.71E−02	6.05E−02	2.04E−03	1.15E−02	2.78E−02	2.50E−02	2.32E−01	4.95E−01	2.61E−01	47.2
CH_4	8.94E−02	4.46E−02	5.06E−02	2.03E−03	1.15E−02	2.78E−02	2.50E−02	2.32E−01	4.83E−01	2.49E−01	48.4
CH_4, biogenic	0	2.55E−03	9.81E−03	5.61E−06	0	0	0	0	1.24E−02	1.24E−02	0
N_2O	7.77E−03	2.29E−03	6.40E−03	7.22E−05	3.49E−04	8.42E−04	5.64E−03	4.78E−03	2.81E−02	2.33E−02	17.2
All CO	2.91E−01	9.92E−02	2.95E−01	7.71E−03	2.24E−03	5.42E−03	2.92E−02	2.97E−01	1.03	7.22E−01	29.7
CO	2.91E−01	2.66E−02	1.45E−02	7.55E−03	2.24E−03	5.42E−03	2.92E−02	2.97E−01	6.73E−01	3.69E−01	45.2
CO, biogenic	0	7.26E−02	2.80E−01	1.60E−04	0	0	0	0	3.53E−01	3.53E−01	0
NMVOC	1.32E−01	1.25E−02	1.32E−02	1.23E−03	1.51E−03	3.64E−03	1.08E−02	1.33E−01	3.08E−01	1.73E−01	43.7
NO_X	1.34	1.31E−01	1.58E−01	1.09E−02	6.74E−03	1.63E−02	2.38E−01	3.67	5.57	1.89	66.1
SO_X	1.10E−01	5.02E−02	1.89E−02	1.04E−03	3.56E−03	8.58E−03	1.11E−02	4.98E−01	7.02E−01	2.03E−01	71.1
All PM	9.56E−02	6.75E−02	2.07E−01	1.98E−03	5.98E−04	1.44E−03	9.17E−03	3.09E−01	6.93E−01	3.81E−01	44.9
PM	9.56E−02	6.70E−02	2.07E−01	1.98E−03	5.98E−04	1.44E−03	9.17E−03	3.09E−01	6.92E−01	3.81E−01	45.0
$PM_{2.5}$[b]	0	5.08E−04	0	0	0	0	0	0	5.08E−04	5.08E−04	0
Energy (MJ/tonne)											
Gross calorific value in pellet	19,426.00	0	0	0	0	0	0	0	1.94E+04	1.94E+04	0
Renewable	21.76	468.80	1,576.52	11.97	2.78	6.71	6.08	45.38	2.14E+03	2.08E+03	2.7
Nonrenewable	877.05	367.99	148.65	11.99	112.16	270.61	244.94	2,198.09	4.23E+03	2.02E+03	52.2

[a] To obtain life cycle values for local pellets just omit the port operation and marine transportation

[b] $PM_{2.5}$ emission was available only for steam generation thus the values here are the emissions linked to steam generation alone. PM emissions for all other processes are captured under "PM"

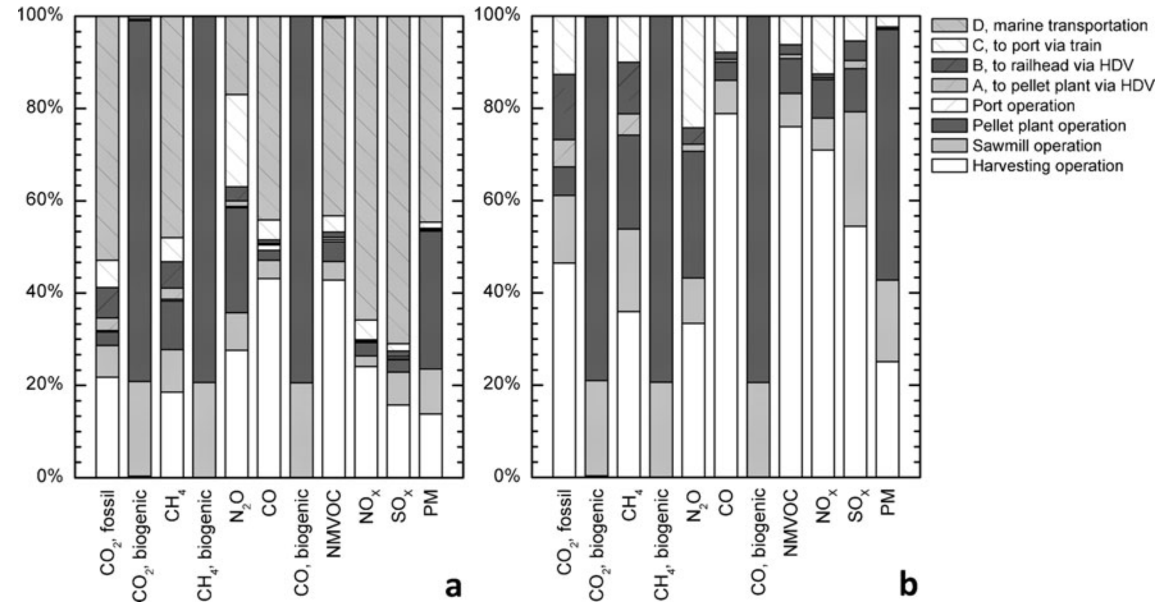


Fig. 3 Stage-wise emissions for **a** exported pellets and **b** pellets to be used locally in BC

(Accredited Laboratory 2007). Furthermore, the amount of nonrenewable energy consumed in the production and delivery of 1 tonne of pellet is compared to the HHV of pellets to give the nonrenewable energy content of wood pellets.

2.6 Comparison with pellets for domestic applications

The environmental footprints including GHG emissions, ecosystem quality and health impacts, fossil nonrenewable energy content, and energy penalty of pellets to be used for domestic (i.e., Canadian, or more likely western Canadian or within BC) applications are calculated and compared with their exported counterparts. The system for domestic-bound pellets is identical to the exported pellets except that port operation and marine transportation are omitted. Since the transportation of pellets from port Rotterdam to end users are not included in this assessment, the delivery of pellets from the port in North Vancouver to end users in Canada is also not considered for consistency.

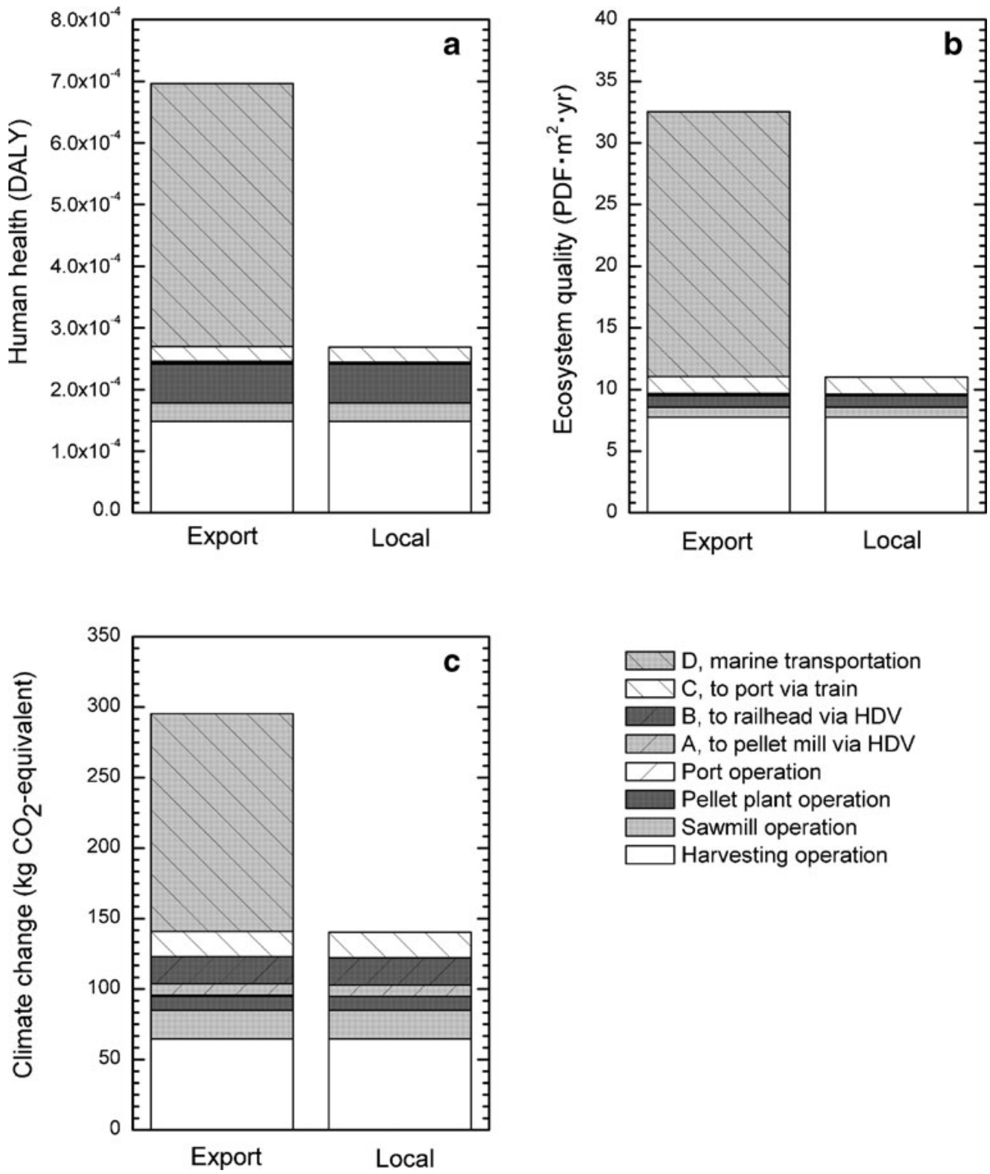
3 Results and discussion

The stage-wise pollutant emissions and emissions over the streamlined life cycle for 1 tonne of exported pellet arriving in Rotterdam and the port in North Vancouver are shown in Table 2 as "export" and "domestic," respectively. Percentage reductions in emissions between the two types of pellets are also presented in Table 2. On top of emissions, stage-wise energy consumptions are also included in Table 2.

It is apparent that without marine transportation and port operation, emissions can be reduced drastically, ranging from 17.2% to 71.1% for different types of pollutants. The reductions of biogenic pollutants are close to zero because marine transportation and port operation generate minimal biogenic emissions. On the other hand, even with low-S HFO, the avoidance of marine transportation can reduce SO_X emissions by 71.1%. Figure 3a, b further illustrates how each processing stage contributes to the emission of each pollutant for exported pellets and pellets to be utilized locally in BC, respectively. For exported pellets, it is apparent that marine transportation contributes to approximately 50% or more for all nonbiogenic emissions other than N_2O. Harvesting stage appears to be the second highest contributor to nonbiogenic emissions. Pellet plant stage contributes approximately 30% and 80% to the life cycle emission for PM and biogenic (including CO_2, CH_4, and CO) emissions, respectively. The high biogenic and PM emissions are linked to the use of wood residues as an energy source for drying within the pellet plant. For pellets to be utilized locally, harvesting stage remains as the hotspot for nonbiogenic emissions while pellet plant is still the main cause for biogenic emissions. These findings show that if further emission reductions are desired within the life cycle of BC wood pellets, other than finding domestic market of these pellets, one should also look into improving the current harvesting and pellet plant operations, may it be better energy efficiency or emission controls.

As impact assessments are linked to emissions, it is not a surprise to see that pellets arriving in Rotterdam have much higher impacts on human health, ecosystem quality, and climate change when compared to pellets arriving in North Vancouver. Figure 4 illustrates how each processing stage and transportation segment add to each type of impacts

Fig. 4 Impact assessment results for 1 tonne of exported pellets and pellets to be used locally in terms of **a** human health impact, **b** ecosystem quality, and **c** climate change



throughout the pellets' life cycle. It is seen from Fig. 4 that marine transportation is responsible for over 50% of the export pellet's impacts on human health (16.8% of the total health impact associated with marine transportation is attributed to PM emissions), ecosystem quality, and climate change. Based on this study, marine transportation generates 154 kg of CO_2 eq per tonne of wood pellets, which lies between the higher value of approximately 450 kg CO_2 eq from Magelli et al. (2009) and a lower value of 60 kg CO_2 eq from Sikkema et al. (2010). By removing transportation D and port operation, human health, ecosystem quality, and climate change impacts can be reduced by 61%, 66%, and 53%, respectively. For pellets to be utilized locally, harvesting operation is by far the most problematic processing stage, contributing to approximately 50% or more to all impacts covered in Fig. 4.

Although the end point comparisons done thus far is reasonable on a relative basis since two scenarios are being compared, it is important to acknowledge that as the analysis performed is a streamlined LCA and only a few selected emissions are included, some midpoint indicators were not calculated and thus not included in the endpoint impact categories. To better illustrate which midpoint indicators were not included in the analysis, Table 3 summarized the stage-wise and total midpoint indicators for both scenarios. Note that to obtain the values for pellets arriving in the port in North Vancouver, the port operation and marine transportation stages were omitted.

In terms of primary energy consumption, every tonne of exported pellets requires 6.37 GJ of energy input, while for pellets remained in BC only 4.10 GJ is required. The stage-wise primary energy breakdown for exported pellets is 14%,

Table 3 Stage-wise and total midpoint impacts endpoint impacts for every tone of pellets arriving port in Rotterdam and North Vancouver

Midpoint impact category	Unit	Harvesting operation	Sawmill operation	Pellet plant operation	Port operation	A, to pellet mill via HDV	B, to railhead via HDV	C, to port via train	D, marine transportation	Total for pellets at Rotterdam	Total for pellets at North Vancouver
Carcinogens	DALY	0	0	0	0	0	0	0	0	0	0
Noncarcinogens	DALY	0	0	0	0	0	0	0	0	0	0
Respiratory inorganics	DALY	1.48E−04	3.04E−05	6.31E−05	1.49E−06	9.34E−07	2.25E−06	2.39E−05	4.26E−04	6.96E−04	2.68E−04
Ionizing radiation	DALY	0	0	0	0	0	0	0	0	0	0
Ozone layer depletion	DALY	0	0	0	0	0	0	0	0	0	0
Respiratory organics	DALY	1.70E−07	1.66E−08	1.77E−08	1.61E−09	2.08E−09	5.01E−09	1.42E−08	1.73E−07	4.00E−07	2.25E−07
Aquatic ecotoxicity	PDF·m^2·year	0	0	0	0	0	0	0	0	0	0
Terrestrial ecotoxicity	PDF·m^2·year	0	0	0	0	0	0	0	0	0	0
Terrestrial acid/nutri	PDF·m^2·year	7.76	0.80	0.92	0.06	0.04	0.10	1.37	21.46	32.53	11.00
Land occupation	PDF·m^2·year	0	0	0	0	0	0	0	0	0	0
Aquatic acidification		–	–	–	–	–	–	–	–	–	–
Aquatic eutrophication		–	–	–	–	–	–	–	–	–	–
Global warming	kg CO_2 eq	64.67	20.38	9.75	0.80	8.00	19.31	18.17	154.28	295.37	140.28
Primary energy consumption	MJ	20,325	836.79	1,725.17	23.96	114.94	277.32	251.02	2,243.46	25,797	23,530

13%, 27%, and 0.4% for harvesting, sawmill, pellet plant, and port operation, respectively. Transportation alone is responsible for 45% of the life cycle energy consumption while just marine transportation alone contributes 35% to the entire life cycle's energy requirement. This finding again proves that marine transportation adds to wood pellet's energy demand and impacts tremendously. If BC pellets can be utilized locally, they will perform much better than pellets that are shipped to Europe as the energy penalty can be lowered from 33% to 21%. Fossil CO_2 emitted can also be reduced by more than 50% if marine transportation is avoided. Furthermore, pellets to be used locally are much more environmentally friendly as the nonrenewable energy consumed to produce and deliver the pellet accounted for only 8.6% of the total energy contained in the pellets compared to 16.4% for pellets that are shipped to Europe.

Although exported pellets perform much worse than pellets to be utilized locally, exported pellets are still superior to other forms of fossil fuels despite the long traveling. The amount of GHG emitted over the entire life cycle, including the end-stage combustion, per gigajoule of fuel utilized for coal burnt in stove, HFO in boilers, diesel in industrial engine, natural gas in boiler, exported BC pellets in pellet stoves, and pellets in local pellet stoves are 99.1 [obtained from US-EI for anthracite burnt in 5–15 kW stove (Swiss Centre for Life Cycle Inventories et al. 2008)], 87.3, 93.9, 56.6, 15.9 and 7.9 kg CO_2 eq/GJ combusted, respectively. Compared to coal, the use of exported pellets and domestic pellets can achieve a GHG reduction of 84% and 92%, respectively. These figures show that despite the long traveling distance, exported pellet still emits less GHG than other forms of fossil fuels when the lifecycles being compared include combustion emissions. A recent case study (Pa and Bi 2011) evaluated the replacement of natural gas in a district heating facility with retrofitted gasification system running on locally produced wood pellets. The result shows that while the GHG emission can be reduced drastically, there are trade-offs such as higher impacts on human health and ecosystem quality.

The fossil CO_2 emission and energy consumption associated with the production and transportation of raw material for the current study are 90 kg CO_2/tonne of pellets and 1,476 MJ secondary energy/tonne of pellets (or 1,736 MJ of primary energy/tonne of pellets), respectively. Comparing with other published studies, these values are much greater. This observation can first be explained by the different types of raw materials used for pellet production in each study. For instance, for Zhang et al.'s study (2010) where harvested logs instead of sawmill residues are used, the energy consumption and emission associated with raw material production and delivery to the gate of pellet plant would only involve the harvesting stage and not sawmill processing.

For pellet plant operation alone, the current study's values for CO_2 emission and energy consumptions are 8.3 kg CO_2/tonne of pellets and 1,579 MJ secondary energy/tonne of pellets (or 1,725 MJ of primary energy/tonne of pellets), respectively. These values are lower than many similar studies, including Magelli et al. (2009), whose numbers are based on Mani (2005) analysis on densification processes using wood residues as drying fuel and their values are similar to that of Zhang et al. (2010). However, it is worth noting that the work of Magelli et al. (2009) uses sawmill residues as pellet's raw material while Zhang and colleagues' utilized harvested logs. The latter's elevated energy consumption and CO_2 emission compared to current study seems to be reasonable as the pellet plant operation in Zhang and colleagues' work involves more extensive size reduction and drying due to the type of raw materials used.

The CO_2 emissions for the entire life cycle without transportation from different studies are quite similar with an exception of a Swedish study (Hagberg et al. 2009). For energy consumption in the entire life cycle without transportation, the value from the current study is the lowest, due to much lower pellet plant energy consumption. However, the work of Świgoń and Longauer (2005) provided similar energy consumption in pellet plant as the current study. Overall, CO_2 emission values from this study appear to be close to other studies while there exist some discrepancies in secondary energy consumptions, especially in energy consumption associated with the pellet plant operation. This study provides a different set of numbers based on industry survey conducted recently, and the inclusion of primary energy, instead of just secondary energy, consumption offers a more complete picture of the entire life cycle. A more detailed comparison with reported numbers is presented in "Electronic supplementary material."

One should also note that this study does not take into account the avoidance of emissions in Europe due to the usage of imported pellets, which is much higher than the emissions associated with the production and delivery of pellets to Europe. For instance, by importing wood pellets from BC for co-firing with coal, emissions linked with coal production and combustion can be avoided. Furthermore, since the effects of emission locations are not considered in this analysis, the human health impact of exported pellets may be overestimated since most of the pollutants are emitted during oversea transportation, away from populated areas.

4 Conclusions

For every metric tonne of BC pellets exported, 295 kg CO_2 equivalent GHG are released. However, if the pellets are to be utilized within BC, the human health, ecosystem quality, and climate change impacts of these BC pellets can be reduced by 61%, 66%, and 53%, respectively. For every tonne of pellets exported to Rotterdam from BC, 6,372 MJ of primary energy is required and approximately 35% of it is related to marine transportation. Approximately 16.4% of the energy in exported pellets is nonrenewable energy, and they have an energy penalty of 33%. For domestically used pellets, the energy penalty is 21% and the nonrenewable energy content is much lower at 8.59%.

Based on the finding of this study, developing local markets and exploring domestic applications for BC wood pellets hold great potential in reducing environmental footprints of BC wood pellets in terms of their human health, ecosystem quality, and climate change impacts. This study also reveals that if further reduction in BC wood pellet's environmental footprints is desired, one should look into improving the harvesting and pellet plant operations. Improvements can be in the forms of better energy efficiency or air emission controls. This database will become available as part of a Canadian Biomass and Bioenergy LCI database that is being developed by the Agricultural Biorefinery Innovation Network.

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